ACCELERATING AND FOCUSING STRUCTURES FOR PIGMI*

D.A.Swenson, E.D.Bush, Jr., R.F.Holsinger,
J.J.Manca, N.Saito**, and J.E.Stovall

Los Alamos Scientific Laboratory, Los Alamos, New Mexico

INTRODUCTION

The National Cancer Institute is supporting a program of accelerator development at the Los Alamos Scientific Laboratory aimed at the extension of proton linac technologies to produce the most suitable Pion Generator for Medical Irradiations (PIGMI). An optimized design of a pion generator suitable for a radiotherapy program at a major medical center has been established, consisting of a 250-keV injector, followed by a 35-meter-long drift-tube linac that accelerates the proton beam to 150 MeV, and an 85-meter-long coupled-cavity linac that accelerates the beam to its final energy of 650 MeV, where the average beam current of 100 microamperes impinges on one or more targets producing abundant quantities of π^- mesons for radiotherapeutic applications.

A number of extensions to proton linac technology are being pursued under the PIGMI program at LASL.[/1/] This paper concentrates on recent developments in three areas relevant to the acceleration and focusing of proton beams, namely, the alternating phase focused (APF) linac structure, the disk and washer linac structure, and small permanent magnet quadrupole lenses. The APF linac structure is being developed for the acceleration and focusing role from the injection energy of 250 keV to a few MeV, where a transition is made to a permanent magnet quadrupole focused linac structure. The disk and washer linac structure is under consideration for the high velocity portion of the design.

THE APF LINAC STRUCTURE

The higher radio frequency (450 MHz) and lower injection energy (250 keV) of the PIGMI linac design seriously compound the problem of beam containment in the first few meters of the structure. The conventional quadrupole-focused drift-tube linac cannot provide the required focusing in this region because of the low velocity of the protons and the limited space available for magnetic quadrupoles.

The prime contender to satisfy the accelerating and focusing requirements in the region below 5 MeV is the concept of alternating phase focusing.[/2-6/] Arrays of such structures have been developed[/7/] which shows promise for acceleration of protons at higher frequencies and from lower energies than currently possible with magnetically focused drift-tube linacs. In these structures, the transverse, as

*Supported by the National Cancer Institute, Division of the Cancer Research Resources and Centers, U. S. Department of Health, Education and Welfare.

**Visitor from Central Research Laboratory of Hitachi Ltd., Tokyo, Japan.

well as the longitudinal, focusing forces are produced by the rf fields. By arranging the drift-tube lengths, and hence gap positions, in an appropriate way, in a more or less conventional standing wave drift-tube linac, the particles can be made to experience acceleration and a succession of focusing and defocusing forces which result in satisfactory containment of the beam in the six-dimensional phase space without dependence on additional focusing fields.

In these structures, the gap-to-gap distances are arranged in such a way that the particles are exposed to the rf fields at some periodic sequence of phase values alternating from side to side of the peak accelerating phase. This periodic modulation in the gap-to-gap distance implies a periodic modulation in the drift tube and gap geometries. These geometries must satisfy a number of constraints related to the dynamics of the particles which are to be accelerated, the resonant frequency of the resulting structure, and certain convenient symmetries.[8]

The beam dynamics computer program, PARMILA, has been modified to generate complete geometrical descriptions of APF structures based on calculations of the particle dynamics, and tables of data from the rf field calculational program, SUPERFISH.[9] Figure 1 shows a selection of the drift tube profiles generated in this manner for the 64 cells of the PIGMI Prototype, which is currently under mechanical design. This structure begins as a pure APF structure and ends, after the introduction of permanent-magnet quadrupole lenses, as a conventional drift-tube linac.[10]

Progress to date has been based on the assumptions that the rf fields are symmetrical about the center of the gaps, and that the peak voltages on the gaps are the product of the cell length times an average axial electric field, which is, at most, a slowly varying monotonic function of axial position. These assumptions are now being tested by both calculations and measurements of the rf field distributions in multicell cavities of the APF type.

Figure 2 shows the electric field distribution in an eight-cell APF tank as calculated by SUPERFISH. A model of this same geometry is being fabricated, and the axial field distribution will be measured by the bead perturbation technique.

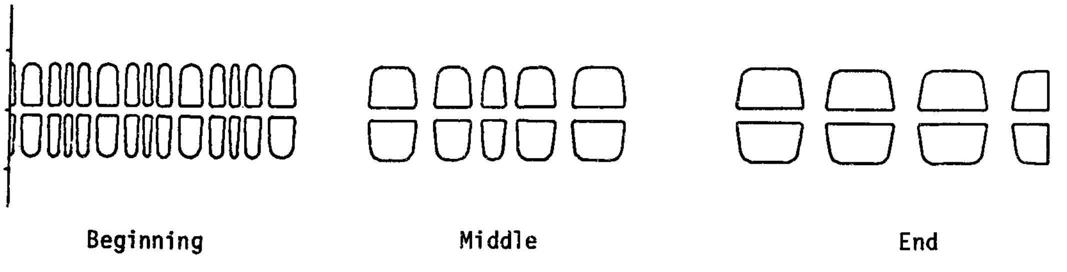

Fig. 1. Selection of drift tube profiles for the PIGMI Prototype.

The axial electric fields were evaluated for the field distribution shown in Fig. 2. These fields were then integrated with the proper weighting factors to evaluate the average axial electric field, the location of the field centroid, and the transit time factor for each of the eight cells.

Even though the cell lengths vary by almost a factor of two, the average axial electric field is constant to better than 0.5 percent, the centroids of the fields coincide with the gap centers to better than 0.01 cm, and the transit time factors agree with those interpolated from half-cell SUPERFISH data to about 0.3 percent.

The geometry of Fig. 2 is made up of 72 straight and circular line segments, the positions of which effect the resulting resonant frequency. These dimensions were chosen on the basis of half-cell SUPERFISH runs to produce a cavity with a resonant frequency of 450 MHz. The resulting resonant frequency was 449.11 MHz.

THE DISK AND WASHER LINAC STRUCTURE

The efficiency of the drift-tube linac structure drops significantly for particle velocities in excess of half the velocity of light. In the region of $\beta = 0.5$ to $\beta = 1.0$, coupled-cavity structures promise better efficiencies for acceleration.

LAMPF is the only major facility to employ such a structure for the acceleration of protons. It uses the so-called "side-coupled" structure invented by Knapp and Nagle at LASL for this application.[11]

More recently, V. G. Andreev of the Radio Technical Institute, Moscow, has discovered and developed the "disk and washer" linac structure.[12] It, too, can be considered as a biperiodic chain of coupled cavities operating in the $\pi/2$ mode.

Two versions of this structure, under investigation at LASL for the high-energy portion of the PIGMI design,[13] are shown in Fig. 3. The first (DAW1) has a planar geometry for the outer portion of the washer, whereas the second (DAW2) has a flared rim for the outer portion of the washer. Both have the same nose cone

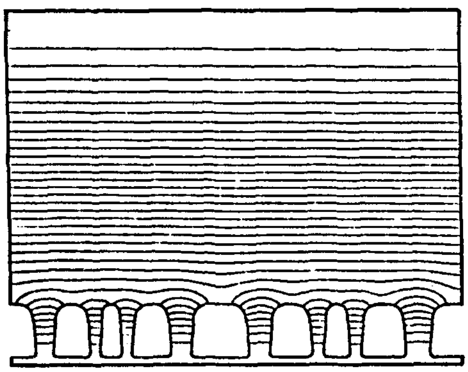

Fig. 2. Eight-cell APF tank with fields.

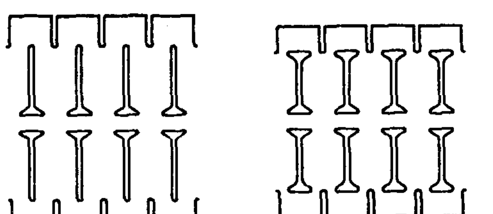

Fig. 3. Disk and washer structure (two models).

geometry near the axis. The primary advantage of the second is the smaller cavity diameter, and a reduction of field strength in the vicinity of the washer supports.

The effective shunt impedance of the disk and washer structure can be within a few percent of that of the LAMPF side-coupled structure, when the losses associated with the coupling slots and cavities of the latter are included. The major advantage of the disk and washer structure is its very high cell-to-cell coupling coefficient, which is approximately 50%, or ten times that of LAMPF. This should result in structures that are less sensitive to manufacturing tolerances, and less sensitive to beam loading effects, than any other known structure with comparable efficiency.

When the structure is terminated at the mid-gap location, it supports a standing wave mode with a strong longitudinal electric field on the axis to serve as the accelerating mode. When the structure is terminated at the mid-washer location, it supports a standing wave mode with most of the stored energy in the outer portion of the cavity to serve as a coupling mode. For the maximum field stability in the accelerating mode, the geometry must be chosen so that the frequencies of these two modes are the same, implying confluence of the dispersion curve at the $\pi/2$ modes.

A most interesting feature of the disk and washer structure is that the entire structure, complete with coupling, has axial symmetry and lends itself to detailed analysis by the rf field calculational program, SUPERFISH.

A whole family of modes for a multicavity system are shown in Fig. 4. The mode designations are based on the biperiodic chain description, where the

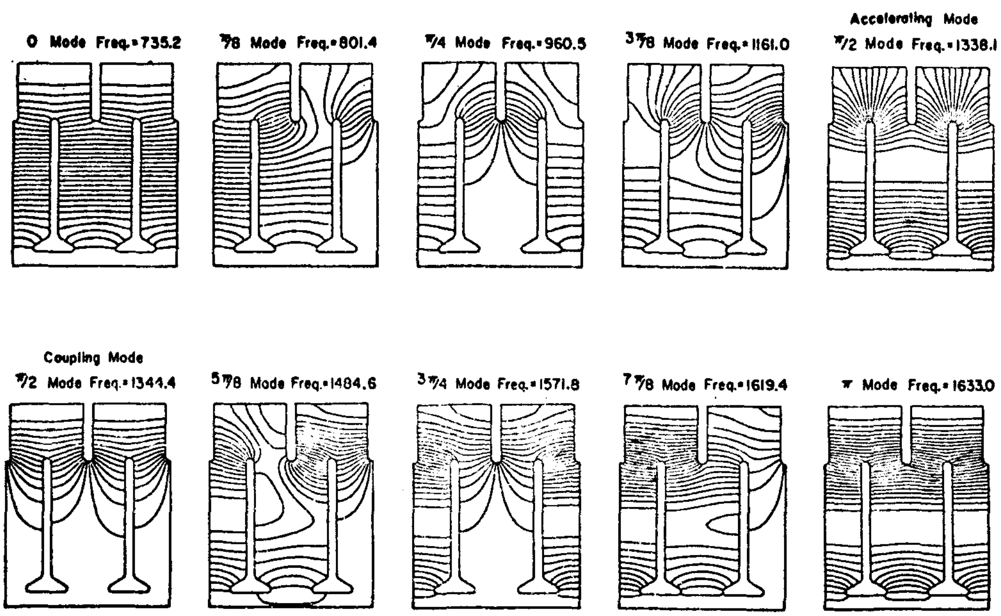

Fig. 4. Family of modes from the disk and washer mode spectrum.

accelerating cavities are interlaced with coupling cavities, and the mode value is the phase shift between nearest neighbors. The basic geometry in Fig. 4 represents one full accelerating cell, two half accelerating cells, and two full coupling cells. The modes which are odd multiples of $\pi/8$ have nonphysical (Dirichlet) boundary conditions on the right-hand side, and can only be excited in physical cavities of twice the length. The mode spectra for these modes has the classic shape, and exhibits a very wide pass band of 900 MHz, corresponding to a coupling coefficient of about 66%.

PERMANENT MAGNET QUADRUPOLE LENSES

Permanent magnet quadrupole lenses are being developed for the drift tubes of the PIGMI linac design.[14] The drift tube diameters are in the range of 7 to 8 cm with a maximum bore radius of 1 cm. The maximum quadrupole gradient for the design is 7 kG/cm and occurs in the low energy end where the drift tubes are quite short. The shortest quadrupole lens with the maximum gradient is in the 43rd drift tube of the PIGMI Prototype which has a diameter of 8 cm, a length of 2.1 cm and a bore radius of 0.6 cm. Studies to date have concentrated on short, high-gradient quadrupoles of this approximate size.

Figure 5 shows the geometrical cross sections of two designs which are currently being investigated. One has circular poles of permanent magnet material, magnetized along a diameter and set in a soft iron return yoke. The other has

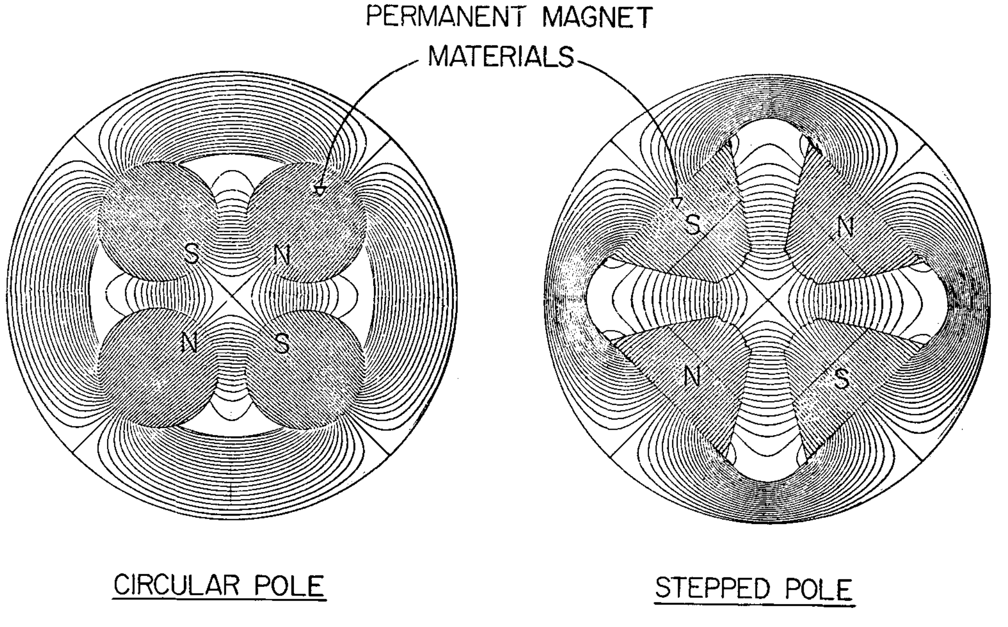

Fig. 5. Permanent magnet quadrupole lens geometries and calculated fields.

trapezoidal poles of permanent magnet material, set in a soft iron yoke, and capped with soft iron poles having stepped profiles.

A family of five yoke assemblies of the circular pole geometry have been fabricated for a pole radius of 0.964 cm, and a range of bore radii corresponding to pole-radii to bore-radii ratios of 1.00, 1.15, 1.30, 1.45 and 1.60. Seventy-two circular poles of three different permanent magnet materials have been procured. One yoke assembly of the stepped pole geometry is being fabricated, and 16 trapezoidal pole pieces are being procured.

The permanent magnet materials that have been investigated are an oriented Alnico-V, a barium ferrite ceramic (INDOX-5), and a rare-earth samarium cobalt (HICOREX-22). The latter two have very linear BH curves in the second quadrant with BH intercepts of 3.8, -3.8 and 9.3, -9.3 kilogauss, kilooersteds respectively.

A new computer code, PANDIRA[15], was developed to aid in the design and analysis of magnetic circuits including permanent magnet materials. The program solves anisotropic magnetostatic circuits by a "direct method" algorithm. The field patterns shown in Fig. 5 were produced by PANDIRA. The permanent magnet materials are described to the program by the BH curve in the second quadrant, the direction of the "easy axis" for magnetization, and the permeability perpendicular to this "easy axis".

The magnetic field gradients and multipole field harmonics have been measured for all combinations of the five circular pole geometries and the three magnet materials. These same quantities have been calculated by PANDIRA for the same five geometries and the latter two materials. Table I presents a comparison of these measured and calculated values. The multipole harmonics are expressed as ratios to the quadrupole (N=2) harmonic normalized to the bore radius. Quadrupole gradients in excess of 10 kG/cm have been achieved for the stronger material and the smaller bore radii.

The stepped pole geometry has been studied with PANDIRA, and the step dimensions have been chosen so as to eliminate the N=6 and N=10 multipole harmonics. These harmonics will be measured when the corresponding model is available.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance of Perry Wechsler on the SUPERFISH and PANDIRA calculations, Fred Humphry on the rf cavity measurements, and Patrick McClellan on the quadrupole field measurements. Special thanks go to Klaus Halbach for his outstanding contributions to the development of SUPERFISH and PANDIRA. The authors acknowledge the continued support and encouragement of Drs. E. A. Knapp and R. A. Jameson.

TABLE I

MEASURED AND CALCULATED GRADIENTS AND MULTIPOLES FOR
FIVE CIRCULAR POLE PERMANENT MAGNET QUADRUPOLE LENSES

R_p/R_b	1.00		1.15		1.30		1.45		1.60	
Bore Radius	.964		.838		.741		.665		.602	
	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.
Material - Alnico-V										
Gradient	1.11		1.47		1.69		2.14		2.41	
N = 6	.2000		.1420		.1280		.1160		.1000	
N = 10	.0510		.0400		.0420		.0420		.0340	
N = 14	.0260		.0150		.0190		.0230		.0210	
Material - Barium Ferrite INDOX-5 (Indiana General)										
Gradient	2.49	2.34	3.04	2.89	3.59	3.37	4.28	3.72	4.77	4.27
N = 6	.1420	.1475	.1050	.1175	.0840	.0908	.0720	.0616	.0550	.0580
N = 10	.0130	.0155	.0060	.1120	.0030	.0081	<.0070	.0055	<.0030	.0079
N = 14	<.0020	.0038	.0014	.0038	.0010	.0037	<.0090	.0057	<.0020	.0068
Material - Samarium Cobalt HICOREX 22 (Hitachi Magnetics Corp.)										
Gradient	6.13	5.89	7.42	7.10	8.64	8.28	10.10	9.42	11.10	10.51
N = 6	.1580	.1545	.1180	.1172	.0900	.0903	.0810	.0710	.0650	.0567
N = 10	.0170	.0166	.0090	.0100	.0060	.0066	.0060	.0046	.0030	.0051
N = 14	.0023	.0025	.0012	.0019	.0006	.0015	<.0031	.0023	.0006	.0031

REFERENCES

1. E. A. Knapp and D. A. Swenson, "The PIGMI Program at LASL," Proc. 1976 Proton Linear Accel. Conf., AECL-5677, 115 (1976).
2. M. L. Good, Phys. Rev., 92 538 (1953).
3. L. B. Mullet, AERE GP/M 147, (1953) (unpublished report).
4. Ia. B. Fainberg, Proc. CERN Symposium on High Energy Accelerators, (1956), p. 91.
5. V. V. Kushin, Atomnaya Energia, Vol. 29, 2, (1970), p. 123.
6. B. P. Murin, Proc. 8th International Conference on High Energy Accelerators, CERN, (1971), p. 540.
7. D. A. Swenson, Particle Accelerators, 7, 61 (1976).
8. D. A. Swenson, "The Geometry of APF", 12 May 1977 (unpublished).
9. K. H. Halbach, R. F. Holsinger, "SUPERFISH -- A Computer Program for Evaluation of RF Cavities with Cylindrical Symmetry," LBL-5040.
10. D. A. Swenson and J. E. Stovall, "Low Energy Linear Structure for PIGMI," Proc. 1977 Particle Accel. Conf. Chicago (1977).
11. D. E. Nagle, E. A. Knapp, B. C. Knapp, "Coupled Resonator Model for Standing Wave Accelerator Tanks," RSI 38, No. 11 (1967).
12. V. G. Andreev, V. M. Pirozhenko, "Parameters of an Accelerating Structure for Proton Linear Accelerator at Higher Energies," Proc. of Radiotechnical Institute, Academy of Sciences, U.S.S.R., No. 9, 1971 (Russian edition).
13. J. J. Manca, E. A. Knapp, D. A. Swenson, "High Energy Accelerating Structure for High Gradient Proton Linac Applications," Proc. 1977 Particle Accel. Conf. Chicago (1977).
14. E. D. Bush, Jr., "Permanent Quadrupole Magnets," Proc. 1976 Proton Linear Accel. Conf. AECL-5677, 363 (1976).
15. K. H. Halbach and R. F. Holsinger, "PANDIRA," to be published.

ДИСКУССИЯ

Ivan Enchevich: Can you tell us, do you have any indications about the stability of the permanent magnets under the irradiation into the accelerator?

D.A.Swenson: Yes, there are data that indicate that the magnetic properties of permanent magnet materials are adequately stable under irradiation conditions of the accelerator.

С.К.Есин: Какова полезная апертура квадруполей с постоянными магнитами, имеющих градиент II кГс/см?

D.A.Swenson: This magnet has a pole tip diameter of 1.2 cm.

G.Willax: Do you have a cost estimate for the accelerator, including its control system (excluded primary supplier like electric installation, cooling system, etc.)?

D.A.Swenson: Preliminary estimates of the costs of the accelerator components, including its control system, and basic building structure are about 8 M.

Н.В.Лазарев: Испытывались ли квадрупольные линзы стержневой конструкции или только линзы с цилиндрическими полюсами?

D.A.Swenson: At the present time, only the circular pole model has been fabricated and tested. A model of the stepped pole geometry is currently in fabrication, and will be tested.

В.П.Джелепов: Имеются ли в США постоянные магниты на градиенты больше чем II,5 кГс/см?

D.A.Swenson: No, not that I know of.

В.А.Тепляков: Как сделана оценка возможного значения ускоренного тока (30 мА) в ПИГМИ ?

D.A.Swenson: The 30 mA that I mentioned is a goal for an eventual PIGMI design. The present structure that we are building should accommodate half of that based on computer simulation calculations with space charge.